Chapter 6

Conclusion

6.1 Summary

This dissertation has presented a quantitative analysis of the impact of tropical cloud systems on latent heating of the atmosphere, radiative forcing of the surface and atmosphere, and the removal of aerosol particles from the atmosphere. These three processes each impact the thermodynamic structure of the atmosphere and the fundamental energy balance of Earth. Because of the important role of clouds and aerosols in the climate system, their successful simulation in climate models is necessary for accurate predictions of climate changes resulting from increasing greenhouse gas and aerosol loading. The dissertation has relied upon observations of cloud cover, precipitation and cloud radiative forcing (CRF) from the Tropical Rainfall Measuring Mission (TRMM) satellite and the METEOSAT-5 geosynchronous satellite. Chapters 3 and 4 have pursued a Lagrangian approach to satellite-based cloud analysis that identifies the boundaries of clouds, tracks them through time, and measures their precipitation and radiative forcing as a function of size and lifetime. The results have revealed the spatial scales at which latent heating and cloud radiative interactions force the climate system. Furthermore, the analysis has demonstrated a strong increase in thermodynamic forcing as the spatial scales of cloud systems increase, illustrated the persistence of giant cloud decks, and quantified systematic biases in the distributions of monsoonal cloud and precipitation in the NCAR CCM3 global model. Chapter 5 uses the knowledge gained about the large mesoscale precipitating structures, and their related biases in model simulations, to refine the role of precipitation in the removal and long-range transport of aerosols.

This chapter provides a brief summary of the results of this dissertation research. The summary is followed by a discussion of potential responses of Earth's hydrological cycle to increases in greenhouse gas and aerosol loading of the atmosphere and the role of model representations of cloud, precipitation and aerosol processes in climate predictions.

Chapter 3 demonstrates that the impact of Indian Ocean monsoonal cloud systems upon the thermodynamic structure of the ocean-atmosphere column increases with the horizontal scale of the system. This occurs, in part, because a larger system impacts a larger volume of air. But more importantly, because the structural properties of larger cloud systems (*e.g.*, cloud liquid water content, cloud thickness and mesoscale precipitation features) are more effective at reflecting solar energy, reducing longwave emission to space and producing precipitation. As a result, it only takes about 20 mesoscale precipitating features (at about 2×10^5 km^2) at a time over the tropical Indian Ocean to provide the observed latent heating driving the winter monsoon circulation. Within the precipitating portions of cloud systems, the magnitude of latent heating exceeds that of shortwave and longwave cloud radiative forcing (CRF) by one order of magnitude. The spatial scales of CRF, however, are much larger, because 75% of the area covered by cloud is not precipitating. Virtually all cloud thermodynamic forcing occurs in overcast decks of cloud spanning more than one model grid cell, even in coarse resolution models, indicating that such structures should be detected in model output. The situation for precipitation, however, is more complicated as the range of typical model grid cells spans the spectrum of rain cell scales. A few grid cells should be completely filled with precipitation; most should not.

Chapter 4 exploits the large spatial scales of monsoonal cloud systems to perform a direct comparison between satellite observed cloud systems and those simulated by a climate model. Large cloud decks spanning numerous model grid cells do occur in the NCAR CCM3 atmospheric model. In fact, the distribution of cloud scales is biased too heavily toward the largest scales, resulting in an overall over-prediction of monsoonal cloud cover. The temporal scales of cloud system processes are revealed in the high-frequency METEOSAT-5 imagery. The area covered by cloud associated with active deep convection within a system peaks up to 15 hours before the total area covered by the cloud system peaks. As cloud material spreads from the convective region, it remains suspended long enough for the overcast cloud deck to maintain its integrity through to the following day, when the diurnal cycling of convection builds back up to supply additional moisture to the middle and upper-level portions of the cloud.

Both chapters 4 and 5 perform comparisons of monsoonal precipitation in satellite observations and atmospheric simulations. Because all but the very largest rain cells are too small to fill a model grid cell it is not possible to directly compare the scales of simulated and observed rain cells. However, there is sufficient information to deduce systematic biases in the simulated precipitation that are related to the scales of precipitating structures. Though the models evaluated in chapters 4 and 5 have different names, the deep convection that produces most of the tropical rain is computed using the same parameterization. The model produces about 60% more monsoonal precipitation than is observed by satellite. However, this rain falls predominantly as light rain. Grid cell averaged rates in the simulations are almost always less than 1 mm hr^{-1}, while as much as 60% of observed rain occurs at higher rain rates. In order to produce more overall rain at lower rain rates, precipitation must occur over a larger area and more frequently in the simulation. The simulated Inter-tropical Convergence Zone (ITCZ) south of the equator in the Indian Ocean consists of a much broader region of moderate precipitation than is observed. As many as 50% more grid cells contain precipitation in the simulations. Meanwhile the regions of greatest rainfall accumulate substantially more rain in the observations than in the model. From chapter 3, it is apparent that the most extreme precipitation occurs in the largest rain cells, which develop substantial mesoscale anvil structures in order to cover areas as large as 10^6 km^2. The organization of precipitation into such structures is largely absent in the model. A modification to the model is tested in chapter 4 that accounts for the evaporation of precipitation below the anvil cloud base as has been observed in mesoscale convective systems (Gamache and Houze 1983). The modification results in a shift in the distribution of precipitation toward the observed distribution, with more extreme rain rates. While the modification is not a complete parameterization of mesoscale convective structures, the result is consistent with the notion that missing mesoscale processes may be a cause of the model bias toward light rain.

Chapter 5 tests a hypothesis that a bias in rain rates, such as that found for monsoonal rain rates in the NCAR CCM3 model, may impact simulated distributions of aerosols. This is tested by combining the MATCH chemical transport model with high-resolution satellite precipitation measurements in simulations of winter monsoon transport of aerosols emitted from the Indian subcontinent. When simulated rain rates are replaced with observed rain rates in the standard model parameterization of precipitation scavenging, only moderate differences are found for aerosol concentrations over the Indian Ocean. A more substantial impact on the aerosol amount is found when the aerosol scavenging is made proportional to the observed grid cell fraction containing precipitation. Under the standard model parameterization, the inclusion of extreme precipitation events does not increase scavenging because of the standard precipitation underestimates the grid cell precipitating fraction for these events. Scavenging according to observed grid cell precipitating fraction substantially reduces aerosol amounts in the Indian Ocean ITCZ region. It also substantially reduces the transport of aerosol beyond the Indian Ocean region. Transport of aerosol to the Southern Hemisphere is substantially impeded by precipitation along the ITCZ in all simulations. In the Northern Hemisphere, away from the source region, aerosol amounts are more than a factor of 2 smaller, compared to the standard model, when the grid cell precipitating fraction observed by satellite is used in the scavenging computation. This effect is most dramatic when scavenging by ice phase precipitation is included, suggesting that long range transport of aerosols is linked to the ability of aerosols to reach the upper-troposphere.

The results of this dissertation have emphasized the importance of large cloud systems embedded with highly energetic precipitation structures. While such systems clearly dominate small and moderate sized systems in contributing to winter monsoon cloud cover, latent heating, radiative forcing, and aerosol removal, note that moderate and small convective clouds are present in much greater numbers. They play a role in important cloud processes such as vertical transport of mass and momentum. During the Indian Ocean Experiment, an elevated aerosol layer was periodically observed at 3 km, and sometimes above the tops of the smaller clouds (Ramanathan et al 2001a). A substantial amount of mass, including haze, is transported vertically in small and moderate clouds over the Indian Ocean.

6.2 Implications for climate and climate change

The emphasis in much of the dissertation work has been on processes occurring within precipitating cloud systems. Such systems, however, do not behave entirely independently. The global surface and atmospheric energy budgets ultimately control the total amount of precipitation, the availability of moisture to condense as cloud, and the frequency and spatial distribution of cloud systems. As the activities of humans have an increasing impact on these budgets through greenhouse gas and aerosol loading of the atmosphere, there is the potential for significant change to the hydrological cycling of the climate system which must be reflected in the structure and thermodynamic forcing of the precipitating cloud systems.

Climate change resulting from the increase in greenhouse gas loading is generally expected to be accompanied by an increase in evaporation and precipitation, a so-called spin-up of the hydrological cycle. Related to the hydrological spin-up is an expected increase in extreme precipitation events, particularly an increase in precipitation associated with individual storms. As surface temperature increases, the saturation vapor pressure in the surface boundary layer of the atmosphere increases and surface evaporation is enhanced (Manabe and Wetherald 1975). This must be balanced by an increase in precipitation if moisture is not to build up rapidly in the atmosphere. This enhanced hydrological cycle is a common response among GCMs in increased greenhouse gas simulations (Houghton et al. 2001). Enhanced precipitation could result from increases in the frequency of rain events, or a shift in the intensity of rain events, or both (Karl and Knight 1998). An analysis of daily accumulations of rain at meteorological stations in the U.S. has documented an increase in both temperature and precipitation, with a large increase in the portion of the precipitation resulting from extreme precipitation events (defined as >50.8 mm hr^{-1}; Karl et al. 1995). As discussed above, TRMM data from the winter monsoon indicate that biases in the CCM3 model are present in both the mean rain rate and the distribution of rain rates. The simulated hydrological cycle is faster (at least in the Indian Ocean region) than observed, resulting in a higher amount of total precipitation. Conversely, extreme precipitation events are less frequent. In order for the model to provide quantitative predictions of changes in hydrological cycling and high-frequency precipitation variability, the sources of such biases must be determined. Enhancing local evaporation of falling precipitation within simulated clouds was shown in chapter 4 to improve the representation of the rain rate distribution, though it had little impact on the total amount of precipitation in the region. The distribution and rate of convergence of low-level water vapor is perhaps a bigger influence than local cloud physics on the overall rate of hydrological cycling in the region. Inter-comparisons, such as presented here of instantaneous or hourly rain rates between models and observations must be extended to more regions and time periods. Though this study has focused on a region of predominantly ocean, it is land areas and the societies and ecosystems they support that are of principal interest in studies of precipitation variability.

Aerosols introduce additional perturbations to the hydrological cycle. The dominant interaction between rainfall and aerosols is that of precipitation scavenging. Indeed, precipitation scavenging is the principle mechanism for removing aerosols from the atmosphere. Evidence of the efficient removal of aerosols in tropical precipitating cloud systems is offered in chapter 5. Though the presence of extreme precipitation events in the observed rain rate distribution has little effect on the aerosol removal rate under the standard scavenging parameterization, aerosol removal is substantial increased along the Indian Ocean ITCZ when the removal rate is tied directly to the observed spatial coverage of precipitation. This results from the large spatial coverage of the most intense precipitating structures. This scavenging study, however, is just a first step in understanding and simulating the interactions between aerosol and precipitation, as the scavenging parameterizations explored here do not account for many potential microphysical interactions. For example, urban and industrial pollution has been demonstrated to suppress precipitation (Rosenfeld, 2000). Plumes containing small aerosol particles can nucleate droplets that are smaller than 14μm, which do not commonly coalesce into precipitation sized drops. This effect, however, may depend on the details of the aerosol size distribution, as a relatively few large particles, such as sea salt spray, may override precipitation suppression (Rosenfeld et al. 2002). Such microphysical impacts on precipitation have only been verified in case studies.

Finally, aerosols may impact the hydrological cycle through their radiative forcing. The direct effect of bright aerosols, such as sulfates, is a surface cooling of 0.1 - 1 W m^{-2} globally (Houghton 2001), as a portion of the sunlight that would have been absorbed at the surface is reflected back to space. The addition of black carbon in aerosol, however, can lead to significant solar absorption in the aerosol layer, leading to a radiative heating of the atmosphere. Such heating enhances the surface cooling by further reducing the amount of solar radiation available for surface absorption. These radiative forcing effects can be quite significant regionally. The haze layer over the Indian Ocean during winter 1999 was estimated to cause an average atmospheric warming of +18 W m^{-2} and surface cooling of -20 W m^{-2} (Ramanathan et al. 2001a). Such a surface cooling can impact the hydrological cycle by impacting the surface energy budget. The surface is principally cooled by evaporation (Kiehl and Trenberth 1997; see also discussion in chapter 1, section 1.1). A substantial reduction in solar energy at the surface reduces the amount of required evaporation, and leads to a spin down of the hydrological cycle (Ramanathan et al., 2001b). While aerosol radiative cooling has been determined to compensate for a portion of greenhouse gas warming (Kiehl and Briegleb 1993), it remains to be determined if aerosols may compensate globally for changes in the hydrological cycle. Nevertheless, a test of the global response to the wintertime Indian Ocean aerosol forcing in a GCM found a tropics-wide reduction in evaporation, although locally precipitation increased owing to the low-level aerosol heating (Chung et al. 2002).

Placing aerosols on par with greenhouse gases as an agent for global change puts a premium on unraveling the complex interactions between aerosols, cloud droplets and global hydrology. Quantitative global assessments and future predictions of aerosol forcing of climate will require a reasonable representation of precipitation scavenging, which clearly requires a proper simulation of the spatial distribution of precipitation. Potential feedbacks, however, between aerosols and precipitation substantially complicate the problem.

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